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Interocular suppression is gated by interocular feature matching

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Abstract

We present a new form of contrast masking in which the target is a patch of low spatial frequency grating (0.46 c/deg) and the mask is a dark thin ring that surrounds the centre of the target patch. In matching and detection experiments we found little or no effect for binocular presentation of mask and test stimuli. But when mask and test were presented briefly (33 or 200 ms) to different eyes (dichoptic presentation), masking was substantial. In a 'half-binocular' condition the test stimulus was presented to one eye, but the mask stimulus was presented to both eyes with zero-disparity. This produced masking effects intermediate to those found in dichoptic and full-binocular conditions. We suggest that interocular feature matching can attenuate the potency of interocular suppression, but unlike in previous work (McKee, S. P., Bravo, M. J., Taylor, D. G., & Legge, G. E. (1994) Stereo matching precedes dichoptic masking. *Vision Research, 34*, 1047) we do not invoke a special role for depth perception.

Keywords: Human vision; Interocular suppression; Inhibition; Dichoptic masking; Contrast matching

1. Introduction

When one stimulus (the mask) degrades the visibility of another stimulus (the test), masking is said to occur. One widely known example of masking is when the mask and test stimulus are processed by the same detecting mechanism; a process that is sometimes referred to as *within-channel masking*. In this case, the mask interferes with the detectability of the test stimulus by lessening the signal to noise ratio in the detecting mechanism, either by compressing the signal or by increasing the noise level (Legge & Foley, 1980; Wilson, 1980). But another example is *cross-channel masking*. Here, the test and mask excite different visual mechanisms, but masking occurs through inhibitory interactions. [1] This form of masking has been used to explain threshold elevation produced by a superimposed cross-channel mask (Foley, 1994; Zenger & Sagi, 1996; Holmes & Meese, 2004; Meese, 2004; Meese & Holmes, 2002; Ross, Speed, & Morgan, 1993), a superimposed dichoptic mask (Meese, 2003; Meese & Hess, 2004) and a surrounding monocular or binocular annular mask (Bruce, Green, & Georgeson, 2003; Snowden & Hammett, 1998). Recently, Meese & Hess (2004) performed contrast matching and detection experiments in which annular surrounds were also found to be effective dichoptic masks.

In this paper we also perform contrast detection and contrast matching experiments and show that

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[1] Another suggestion is that what looks like cross-channel masking in visual cortex is in fact within-channel masking within the LGN (Carandini, Heeger, & Senn, 2002; Freeman, Durand, Kiper, & Carandini, 2002).

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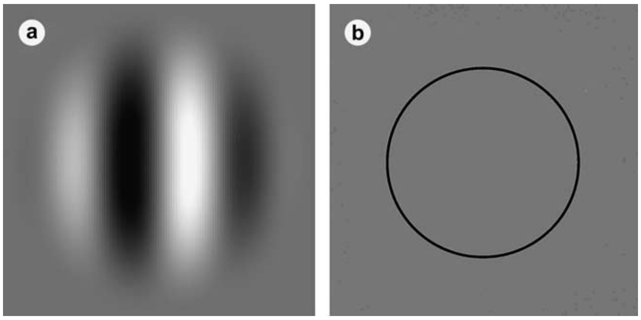

Fig. 1. High contrast examples of test (a) and mask (b) stimuli used in the main experiment. The spatial frequency of the test stimulus was 0.46 c/deg and the diameter of the mask was 1.5 cycles of the test stimulus.

dichoptic surround masking remains effective when the mask stimulus is changed to a simple ring (Fig. 1(b)). The dichoptic ring produces threshold elevation and attenuates the perceived level of contrast for suprathreshold test patches. This effect is perhaps related to that found by Levelt (1965a, 1965b), where a ring presented to one eye shifted the contribution to binocular luminance summation away from the other eye and towards the region surrounded by the ring in the first eye.

We then use our stimulus to further investigate an issue relating dichoptic masking and binocular feature matching. McKee, Bravo, Taylor, & Legge (1994) found that a high contrast bar in one eye was an effective dichoptic mask for a superimposed low contrast target bar being detected by the other eye. In a further experiment they presented a second high contrast bar to the same eye as the target and adjacent to it. In a control condition this bar produced no monocular effects of its own but intriguingly, when presented along with the original dark bar in the other eye it was found to release dichoptic masking. McKee et al. argued that the two dark bars prompted a binocular match, but because they had non-zero disparity the dark bar was seen in a different depth plane from the target bar. The authors supposed that it was this perceived shift in the depth plane of the masker that released dichoptic masking and concluded that stereo matching must precede dichoptic masking.

Because McKee et al. (1994) used a dichoptic mask presented to a corresponding point with the target, their crucial manipulation with the second dark bar inevitably resulted in a condition of non-zero disparity and perception of depth. Our ring mask, on the other hand, provides a condition in which dichoptic masking is possible without superposition of mask and test stimuli. This allows for a psychophysical test similar to that performed by McKee et al. (1994) but one in which stereo disparity cues do not drive a three-dimensional interpretation of the stimulus.

2. Methods

2.1. Equipment

Stimuli were generated using the framestore of a CRS VSG2/3 operating in twin palette mode to produce pseudo 12-bit grey-level resolution. Stimuli were presented on a display monitor, which had a mean luminance (L) of 60 cd/m^2 and was gamma-corrected using lookup tables. The experiments were run under the control of a PC. Stimuli were viewed through a stereoscope with front-silvered mirrors and an effective viewing distance of 52 cm. The visible region of the display consisted of a 256 pixel square array for each eye which subtended a visual angle of 11.5 deg. The frame rate of the monitor was 120 Hz, which gave a picture refresh rate of 60 Hz due to frame-interleaving of mask and test stimuli.

2.2. Stimuli and conditions

Our main test stimulus was a sine-phase patch of vertical sine-wave grating, multiplied by a raised cosine function with a central plateau. It had a spatial frequency of 0.46 c/deg and an envelope function whose rising and falling parts were each 50 pixels wide (2.25 deg) and whose intermediate plateau width was 24 pixels (1.08 deg). This produced a test stimulus with half a cycle of undamped grating, and an envelope with full width at half height of 1.5 cycles (Fig. 1(a)). The main mask stimulus was a dark ring (41 cd/m^2) with a width of one pixel and a diameter equal to that of the full width at half height of the test stimulus envelope (Fig. 1(b)).

In a monocular condition, test and mask were presented to the same eye. In a binocular condition, test and mask were presented to both eyes. In a dichoptic condition, test and mask were presented to different eyes. In a half-binocular condition, the mask was presented to both eyes, but the test was presented to one eye.

In all experiments a small fixation spot was displayed in the centre of the display region for each eye, and in most experiments, stimulus duration was 200 ms.

Deviations from these basic stimulus conditions are described in the subsection *preliminary experiments*.

2.3. Contrast detection

In the contrast detection experiments, thresholds were measured using a two-interval forced-choice (2IFC) technique, where the mask stimulus appeared in both test intervals and the test stimulus appeared in one, chosen at random. Observers used two buttons of a mouse to indicate which interval contained the test stimulus and were given auditory feedback (a short tone) to indicate the correctness of their response. Stimulus contrast was controlled in log steps by a 3-down, 1-up staircase procedure (Wetherill & Levitt, 1965).

2.4. Contrast matching (nulling)

In the contrast matching experiments, the contrast of the test stimulus was adjusted in log steps by a 1-up 1-down staircase procedure (Meese, 1995) to match the perceived contrast of an unmasked reference stimulus over a range of reference contrasts. The order of test and reference stimuli was randomised and the observer used two mouse buttons to select the test interval that appeared to contain the higher test contrast. No feedback was given. Preliminary contrast detection experiments ensured that the lowest contrast used for the reference stimulus was always above detection threshold.

2.5. Psychometric functions and order of conditions

In all cases, psychometric functions were measured using pairs of interleaved staircases (Cornsweet, 1962) with a step size of 3 dB (where dB units are 20 times the log increment/decrement of Michelson contrast) for the detection experiments and 2 dB for the matching experiments, and were fit using probit analysis (the data were fit by a cumulative log-Gaussian function). For the detection experiment, threshold was taken to be the 75% correct point on the psychometric function. For the matching experiments, the point of subjective equality was the 50% point on the psychometric function. For both types of experiment, the analysis was based on the data gathered from the last 12 reversals of each staircase (i.e., from 24 reversals per staircase pair). Larger step sizes were used for an initial pair of staircase reversals but the data from these preliminary stages were discarded from the analysis. In the preliminary experiments, the analysis was based on data gathered from a single pair of staircases for each stimulus condition, and different conditions were performed in a random order. In these cases, standard errors are those estimated by probit analysis (Finney, 1971; McKee, Klein, & Teller, 1985). In the main experiment, data were averaged across four estimates (i.e., four pairs of staircases) for detection and at least two estimates for matching, and error bars show the standard error of these distributions. For the detection experiment, the order of conditions was blocked and for the matching experiment the experiment was performed twice, once with trials blocked and once with trials interleaved across stimulus conditions (binocular, dichoptic and half-binocular).

2.6. Observers

The two authors (TSM and RFH) served as observers. They both wore their normal optical correction, and were well practised at the tasks before data collection began.

3. Ring masking

3.1. Preliminary experiments

We first consider a series of preliminary experiments aimed to examine basic stimulus parameters of our masking paradigm. In the first experiment, contrast matching of monocular stimuli in the presence of monocular and dichoptic ring masks was compared. Results are shown in Fig. 2(a) for TSM. (Very similar results for both conditions were found for RFH. For the binocular condition these can be seen by looking ahead to Fig. 4.) The ring had very little effect in the monocular case, but produced substantial suppression in the dichoptic case.

One possibility is that the dichoptic masking seen here is related to binocular rivalry. Typically, rivalry takes a couple of hundred milliseconds or so to build up (Anderson, Bechtoldt, & Dunlap, 1978; Wolfe, 1986). However, when we reduced the stimulus duration from 200 to 33 ms, we found that suppression remained (Fig. 2(b)), indicating that the process we have revealed is much faster than that usually associated with binocular rivalry, though the possibility remains that this might be a glimpse of the rivalry process at an initial stage.

As mentioned in the methods section, the diameter of the ring was the same as the diameter of the hole in the dichoptic mask. This matches the diameter of the test stimulus at the half-height of its envelope and we wondered how critical this was for suppression. To test this we varied the diameter of the ring mask (see Fig. 2(c)). Suppression was greatest for the condition that we had already considered (diameter = 1.5 test cycles), but was also clearly evident for smaller diameters (0.4 and 1.1 test cycles) and a larger diameter (2.3 test cycles). There was also some evidence for suppression when the diameter of the ring mask was 4.1 cycles. (Note that the full width of the test stimulus was 2.6 cycles). Thus, dichoptic suppression does not require that there be spatial overlap between the mask and test stimulus.

In previous work using windowed gratings in annular surrounds (Meese & Hess, 2004) we found that dichoptic suppression was generally greater for the lower spatial frequency (0.46 c/deg) that we tested. However, in that work, the size of the test stimulus was scaled by its spatial frequency and so it was not clear whether the important parameter was spatial frequency or stimulus size. Fig. 2(d) shows results for two test stimuli with a spatial frequency of 1.84 c/deg. In one condition, the stimulus had the same spatial envelope as the 0.46 c/deg stimulus (large solid circles) and in another condition the envelope was scaled with spatial frequency (small open circles). In both cases, the diameter of the ring mask was the same as the diameter of the spatial envelope of the test stimulus at half-height. For both

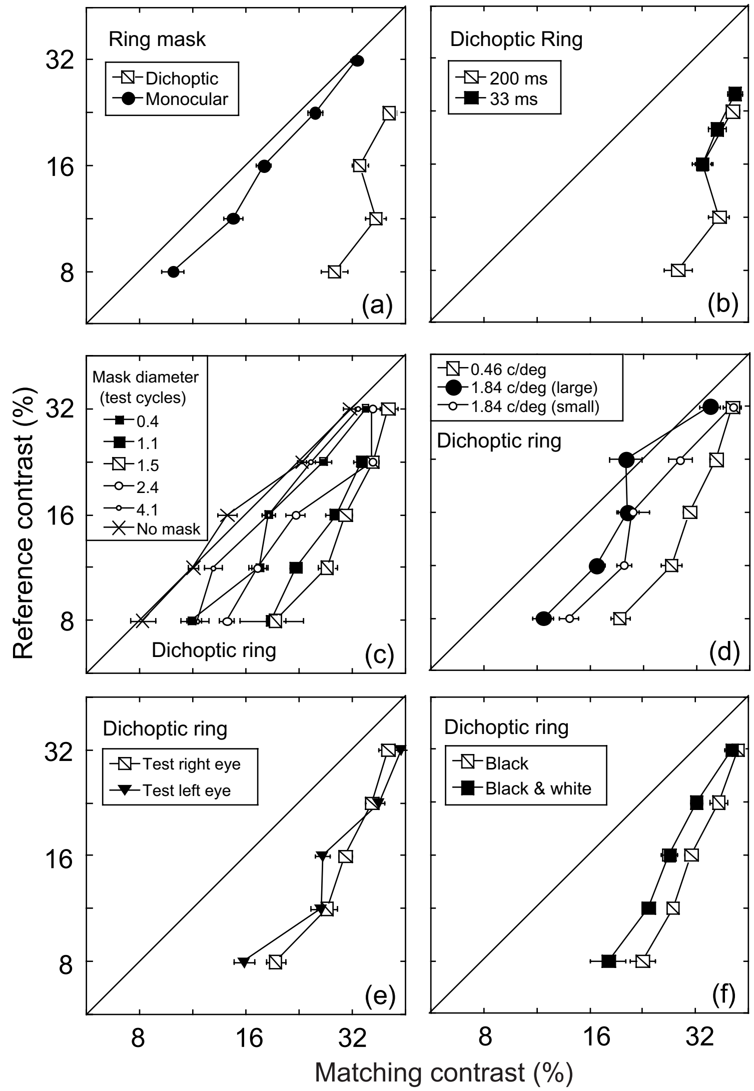

Fig. 2. Contrast matching for the preliminary experiments. Except where stated, the test and mask stimuli were as shown in Fig. 1, and the test stimulus was presented to the right eye. (a) Comparison of monocular and dichoptic stimulus presentation. (b) Comparison of stimulus duration for the dichoptic condition. The 200 ms data are replotted from the previous panel. (c) Effect of ring mask diameter on dichoptic masking. In a control condition (×-symbols) there was no mask. (d) Effects of size and spatial frequency of test stimulus on dichoptic masking. For the circle symbols the patch of test grating had a spatial frequency of 1.84 c/deg. The test patch was either the same physical diameter as before (solid symbols), or was reduced by a factor of 4 so as to have the same number of cycles as before (open circles). In the first case, the mask ring had the same diameter as before and in the second case its diameter was also reduced by a factor of 4. The square symbols are replotted from the previous panel. (e) Comparison of the eye to which the test stimulus was presented. The solid triangles are for when the test and reference were presented to the left (non-dominant) eye and the dichoptic mask was presented to the right (dominant) eye. The square symbols are for a condition in which stimulus presentation was the other way around and are replotted from the previous panel. (f) Comparison of ring masks with different space averaged luminance levels. In one condition (open squares), the stimulus was a dark ring of one pixel width as before (i.e., the same condition as the open squares in previous panels). In another condition (solid squares), the ring was two pixels in width. An inner ring was identical to that in the first condition but the outer ring was bright. The space averaged luminance of this compound ring was the same as the mean luminance background. In all panels error bars are ±1 SEM and the observer was TSM.

configurations, suppression was less than it had been for the 0.46 c/deg condition (square symbols, replotted), indicating that test spatial frequency is the important parameter.

In all of the previous experiments, the test stimulus was presented to the observer's preferred eye in the dichoptic masking conditions. Fig. 2(e) shows that very similar results are obtained when the experiment is performed the other way around: with the test stimulus in the non-preferred (left) eye and the dichoptic mask in the preferred (right) eye.

In all of the previous experiments, the ring mask contained a luminance component (0 c/deg) and (low amplitude) low spatial frequency components in addition to the high spatial frequency components associated with the ring's contour. In principle, it could be these low

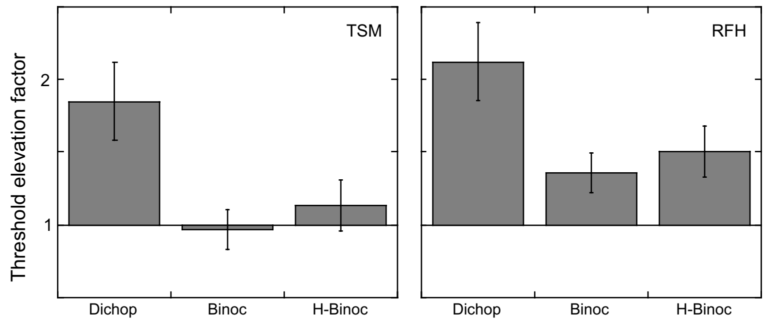

Fig. 3. Threshold elevation from the detection experiment. Each tick mark on the ordinate represents a threshold elevation factor of $\sqrt{2}$. Data are averaged across eyes (for dichoptic and half-binocular conditions) and error bars are ±1 SEM. Monocular detection thresholds were 2.52% for TSM and 2.92% for RFH and provided the baseline for the dichoptic and half-binocular conditions. Binocular detection thresholds were 1.56% for TSM and 1.45% for RFH and provided the baseline for the binocular condition.

spatial frequency components that were responsible for the suppression in our experiments. To test this we repeated the experiment with a second bright ring placed one pixel inside the first (i.e., the two rings were adjacent). This produced a mask stimulus with a contrast of 32% and effectively eradicated the low spatial frequency components. As shown in Fig. 2(f), the new stimulus remained an effective mask, indicating that the main cause of suppression by our ring masks could not be their low spatial frequency components.

3.2. Main experiment: binocular matching gates dichoptic suppression

In the experiment for which results are shown in Fig. 2(a), we found that dichoptic suppression was greater than monocular suppression. These results suggest a suppressive interaction between the two eyes, which, according to other results above (Fig. 2(b)), occurs over a very rapid time scale. On this view, dichoptic masking (Legge, 1979) occurs due to an explicit stage of suppression (see Appendix A in Meese & Hess, 2004) rather than binocular summation within binocular channels [2] (Legge, 1984). But why should dichoptic masking from the surround be so much greater than binocular masking from the surround? One possibility is that interocular suppression is gated by the monocular matching of image features between the two eyes. Specifically, we suggest that if a binocular match is achieved then the magnitude of dichoptic suppression can be attenuated. As mentioned in the Introduction, there is already some evidence for this from the work of McKee et al. (1994). In their study, binocular matching of mask components placed them in a different depth plane from a test stimulus and this released dichoptic masking. Here we tested this idea further by asking whether simple binocular matching of mask components with zero-disparity is sufficient to release dichoptic masking by a ring. There were three stimulus configurations. Binocular and dichoptic conditions were as before, and a half-binocular condition contained a ring mask presented to both eyes and a patch of test grating presented to one eye only.

3.3. Results

The results of the detection experiment are shown in Fig. 3. For both observers, threshold elevation was greatest for the dichoptic condition and much less for the other two conditions. Fig. 4 shows the results of the matching experiment, where top and bottom panels are for when trials where blocked and interleaved across the three stimulus conditions, respectively. Regardless of this experimental detail, the pattern of results was similar for the two observers. Over the high contrast region explored by this experiment, little or no effect was found for the binocular condition. For the dichoptic condition the effect was substantial, and for the half-binocular condition the results were intermediate. Note that the total contrast energy of the mask was always the same in the binocular and half-binocular conditions (mask presented to both eyes) and was greater than in the dichoptic condition (where the mask was presented to one eye only). In other words, the effects were greatest in the condition with the lowest overall contrast energy in the mask.

4. Discussion

In previous work (Meese & Hess, 2004) we performed dichoptic masking experiments using annular surround masks whose spatial frequency and orientation was different from the test stimulus. Unlike an earlier study that used textured noise as test and mask stimuli (Chubb, Sperling, & Solomon, 1989), we found that the annular

[2] In this paper we use the term 'binocular channel' to refer to a mechanism that receives excitatory input from both eyes. We use the term 'monocular channel' to refer to a mechanism that receives excitatory input from only one eye. With this terminology a monocular channel is permitted to receive inhibitory input from the other eye.

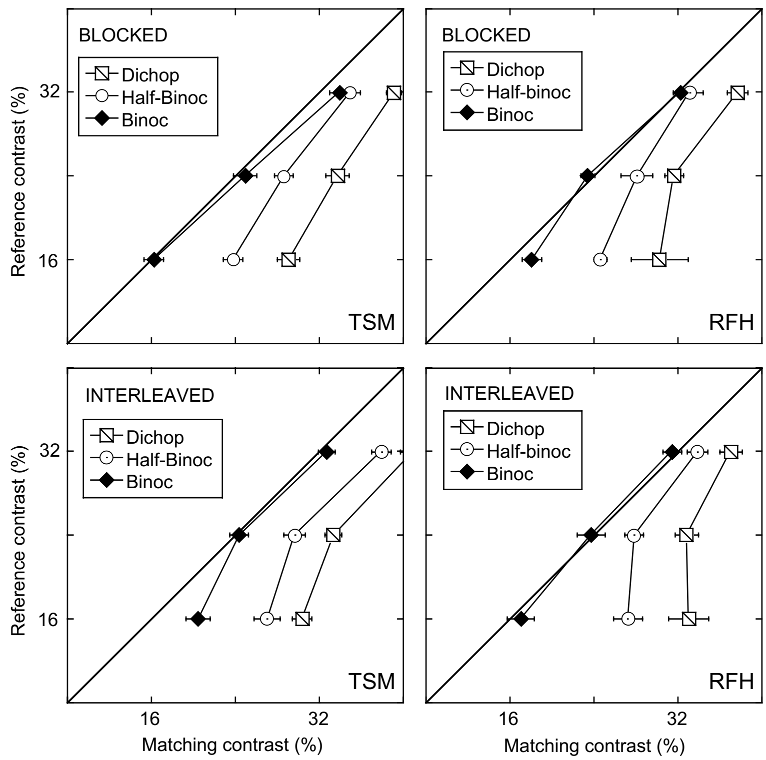

Fig. 4. Contrast matching results for the main experiment. The top and bottom panels are for when trials from the three different conditions were blocked and interleaved, respectively. Left panels are for TSM and right panels are for RFH. For TSM, results are averaged across eye. For RFH, results are for when the test stimulus was presented to the left eye. When the test stimulus was presented to the right eye in the half-binocular condition, the point of subjective equality was close to the highest contrast that could be displayed (47%) using our frame interleaving technique. For the dichoptic condition, it was well beyond this limit. For this reason, the right-eye data for RFH have been omitted from the graphical analysis. Error bars are ±1 SEM.

grating was a very effective dichoptic mask, both at and above contrast detection threshold, particularly when the target had a low spatial frequency. Here we have extended that work and found that the surround need not contain a grating or texture at all, but is effective when a simple thin ring is used. We found that masking was almost abolished in monocular and binocular conditions, and much reduced in a half-binocular condition where the target was presented to one eye and the ring mask was presented to both eyes. Taken together, these results suggest that suppression from a surrounding ring is due to interocular suppression (dichoptic conditions), but that the suppression is reduced by feature matching of the mask between the eyes (half-binocular condition) and further still by feature matching of the test stimulus between the eyes (binocular condition). But what kind of model might be constructed for these effects and how might the gating be achieved?

McKee et al. (1994) assumed that dichoptic masking was a within-channel phenomenon (Harrad & Hess, 1992; Legge, 1979; Levi, Harwerth, & Smith, 1979), and concluded that it came after stereo matching. But our own results are inconsistent with this assumption and do not lead to the same conclusion. First, our contrast matching results are at odds with a within-channel account and point to suppressive interactions. A simple candidate model (see Meese & Hess, 2004) posits a divisive contrast gain control stage (Foley, 1994) for both of the monocular channels prior to excitatory binocular summation. This model also allows for interocular suppressive contributions at the divisive stage from a range of spatial frequencies, orientations, retinal locations and so forth. Second, like McKee et al. (1994), we found that a mask presented to the same eye as a target could release dichoptic masking. But in our experiment there was no binocular disparity, and at no stage did the mask appear in a different depth plane from the test stimulus. [3] Thus, it would seem that simple binocular matching is a sufficient condition to release dichoptic masking. But how can interocular suppression of monocular

[3] We did not perform any objective assessment of depth perception of our stimuli. However, subjectively, our stimuli produced little or no impression that the ring and test patch were at different viewing distances. Furthermore, if the perceived depth plane of the ring and test patch had depended upon the stimulus condition, then this would have been particularly striking when trials from the different conditions were interleaved, as they were in the main experiment. We are confident that there was no obvious trial-to-trial variation in perception of depth in this experiment.

channels follow binocular combination? No doubt, several schemes could be derived to accommodate this, but one simple model feeds back the outputs of binocular channels onto monocular stages where they modulate the divisive input to the gain control. Although different in scope, this idea of cortical feedback is similar to that which has been proposed to account for contrast gain control in primary visual cortex (Albrecht & Geisler, 1991; Heeger, 1992).

In sum, the results from this and a companion paper (Meese & Hess, 2004) do not rule out (i) a within-channel role for dichoptic masking, nor (ii) the involvement of stereo depth in dichoptic masking. However, the present results (i) do require a suppressive account of dichoptic masking and (ii) do not require the computation of depth, suggesting instead that binocular matching is all that is needed to gate the suppression. We see no reason why a similar account could not also be applied to the results of McKee et al. (1994).

Acknowledgments

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